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Title: Studying radiation hydrodynamics in laboratory astrophysics

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Studying radiation hydrodynamics in laboratory astrophysics

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CSAC Review

10/10/2021

Special thanks to my host institutions

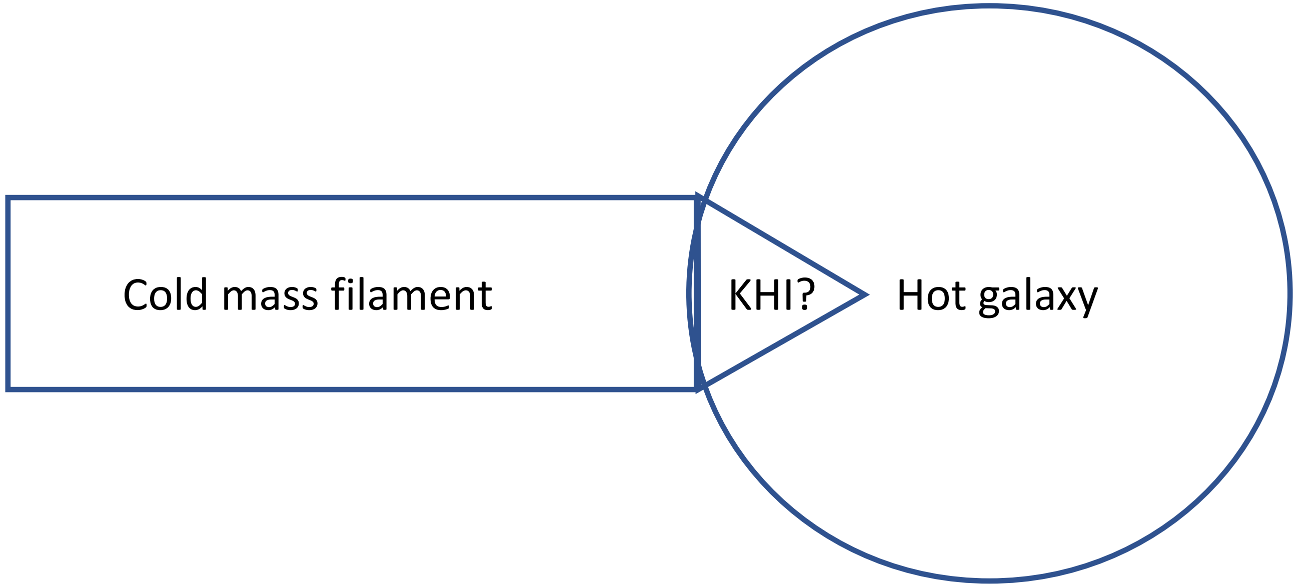
- Final year in the Applied Physics program at University of Michigan (expected by Spring 2022)
- Conducting thesis research at and in collaboration with Los Alamos National Laboratory
- Advisors: **Carolyn Kuranz, R. Paul Drake, Chris Fryer**

Los Alamos NATIONAL LABORATORY

UNIVERSITY OF MICHIGAN

My goal is to help integrate astrophysics and HEDP experiment

- HEDP experiments enable scaled astrophysical studies
  - Experimentally explore difficult observations and theories
  - Mutually beneficial development (hydro, plasma, nuclear physics, etc,.)
  - A promising new field
- How?
  - Kelvin-Helmholtz instability (KHI) in cosmic filaments
  - Supernova shock breakout
  - The COAX experiment
- After each section, I'll tell you why we need to study these things



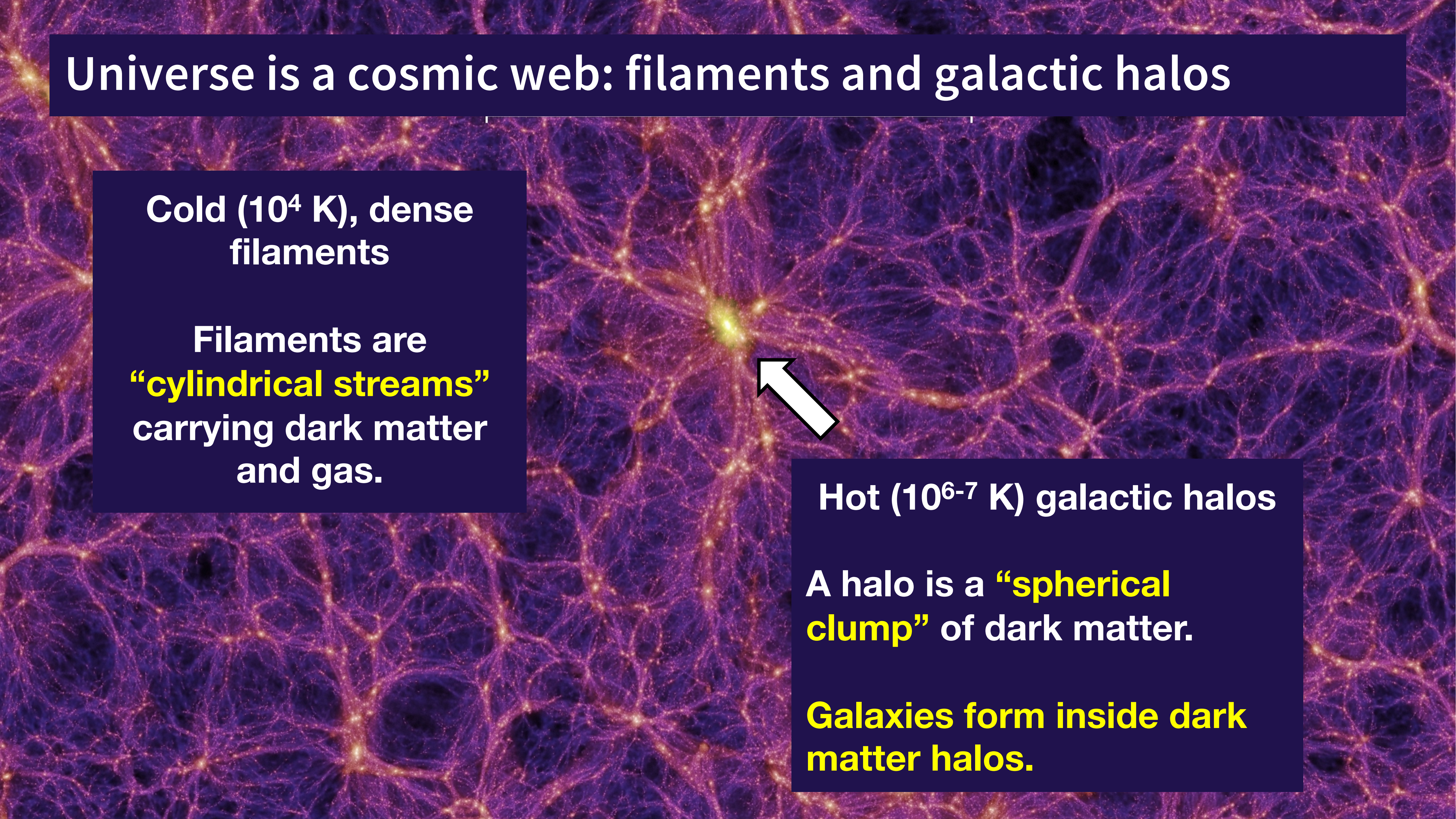
KHI in cosmic filaments

Does KH hinder the cold filamentary mass flows that feed galaxies?

How does radiative cooling affect the KH?

Can an experiment elucidate this phenomenon?

Universe is a cosmic web: filaments and galactic halos



Cold (10^4 K), dense filaments

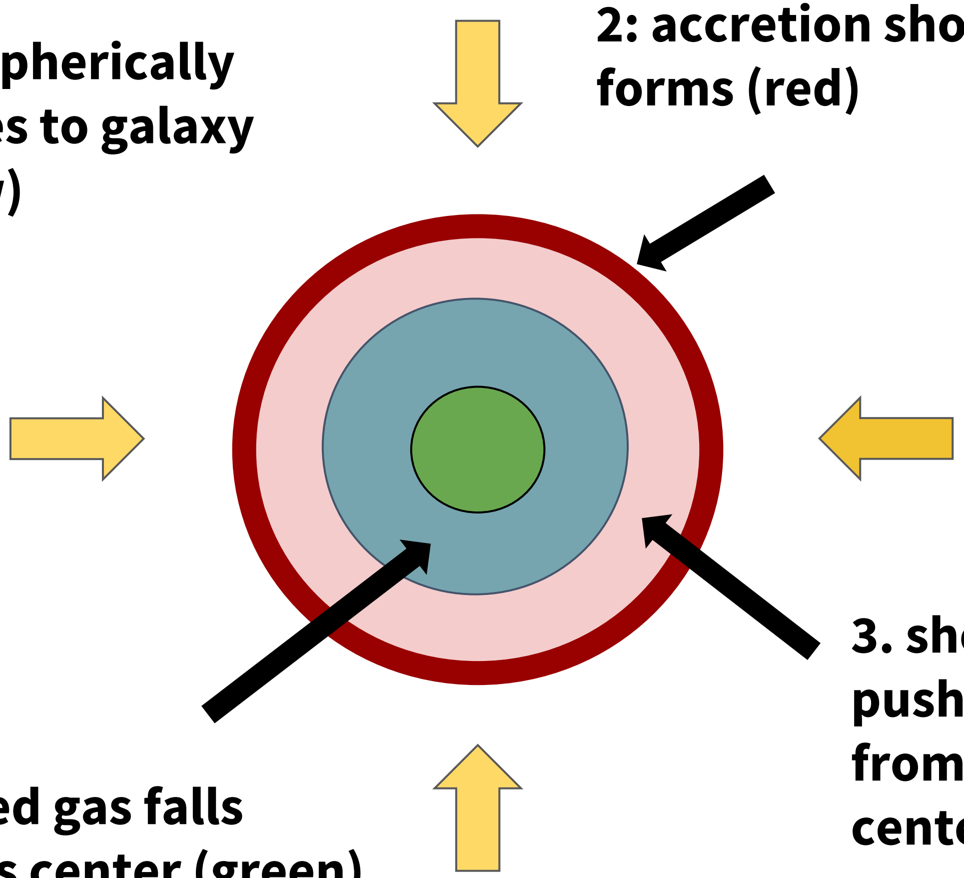
Filaments are **"cylindrical streams"** carrying dark matter and gas.

Hot ($10^{6\text{-}7}$ K) galactic halos

A halo is a **"spherical clump"** of dark matter.

Galaxies form inside dark matter halos.

Galaxies may acquire gas in three different ways



Hot mode

Spherical inflow compresses and forms a shock. Incoming gas gets shock heated.

Cold mode

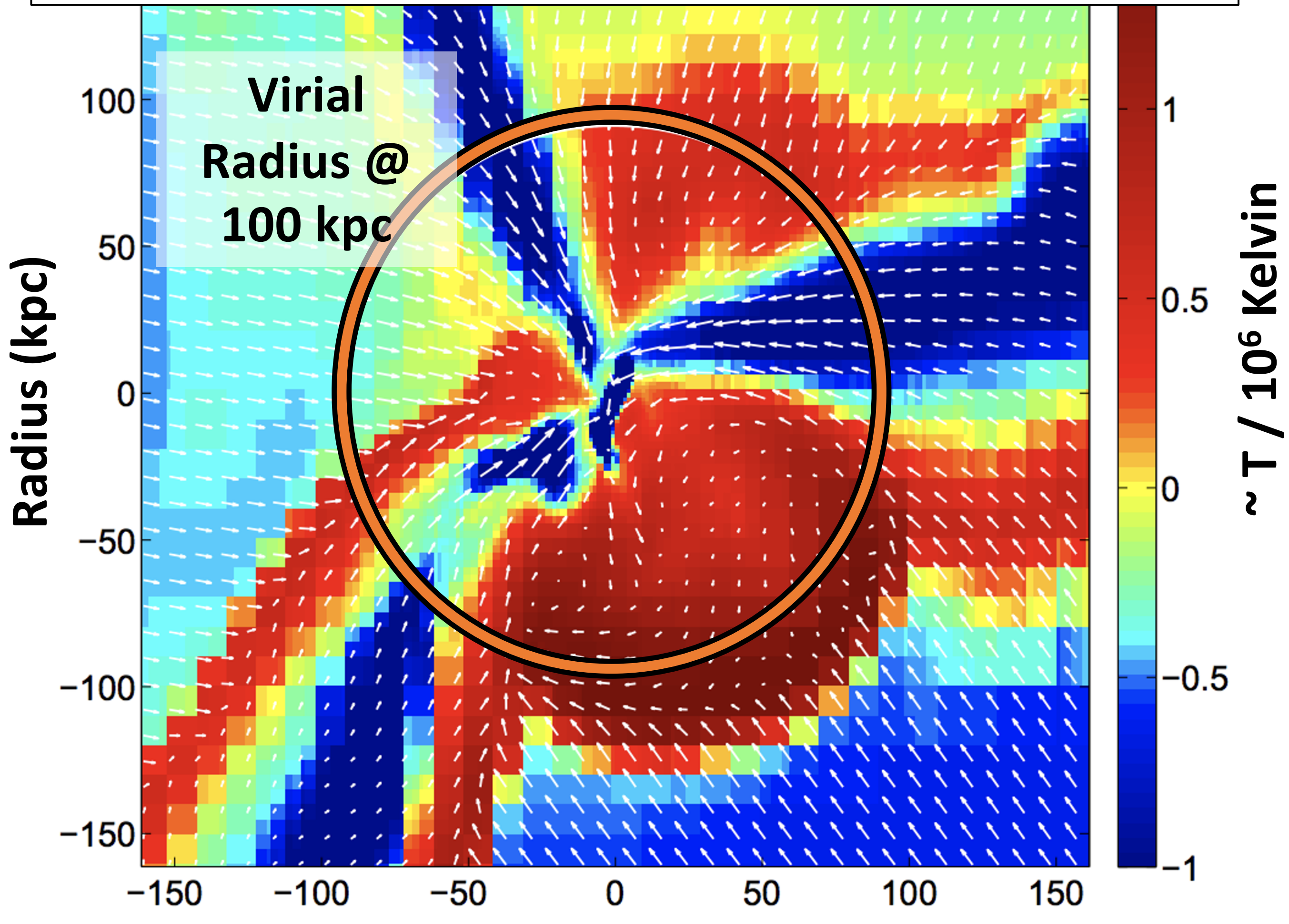
Cold gas flows through filaments in free-fall. No shock forms, gas stays cold.

Cold in hot media

Filaments + accretion shock?

Background/filament interface is KH unstable

Close-up galaxy in simulation: Halo background is red, filaments are blue

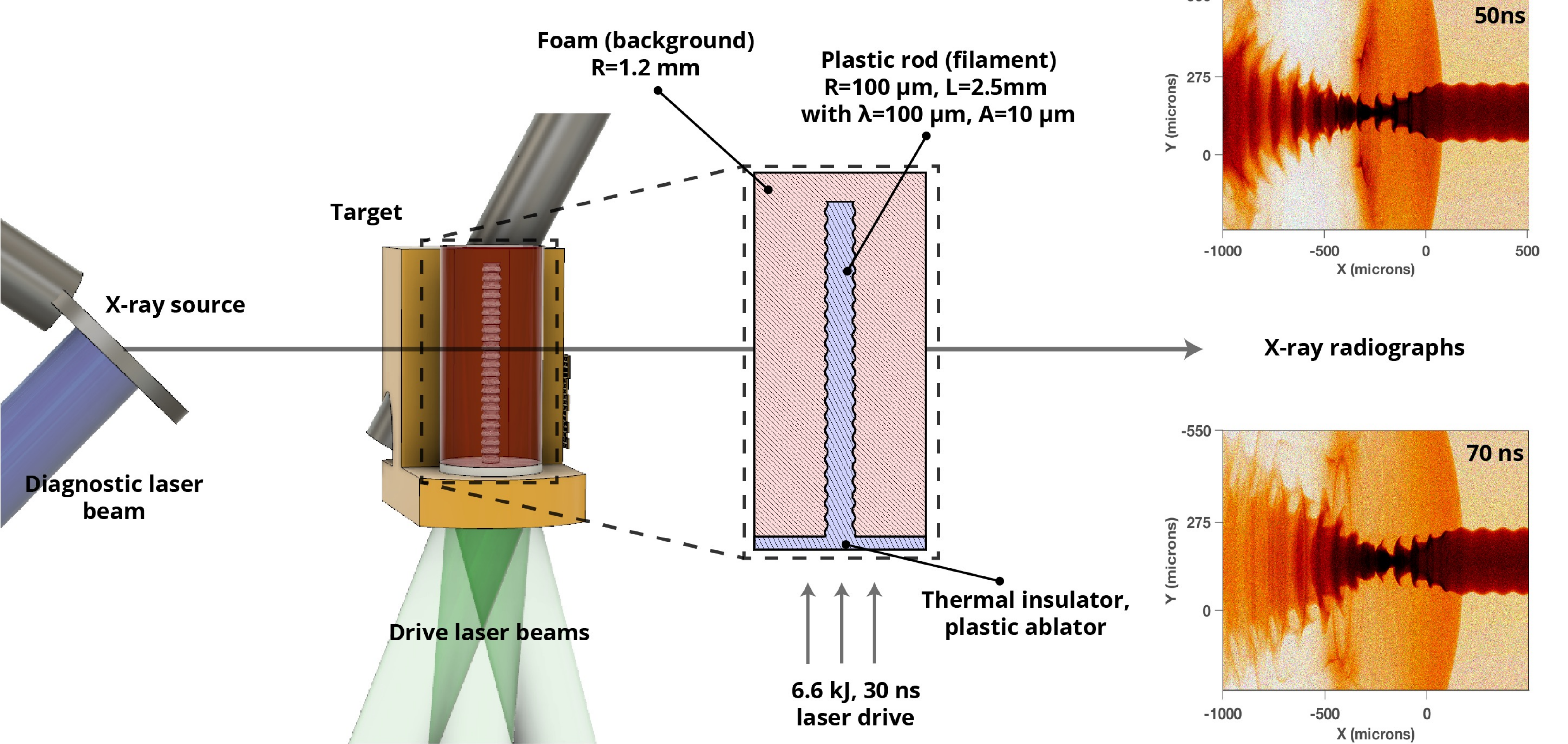


Galaxy simulations do not properly resolve

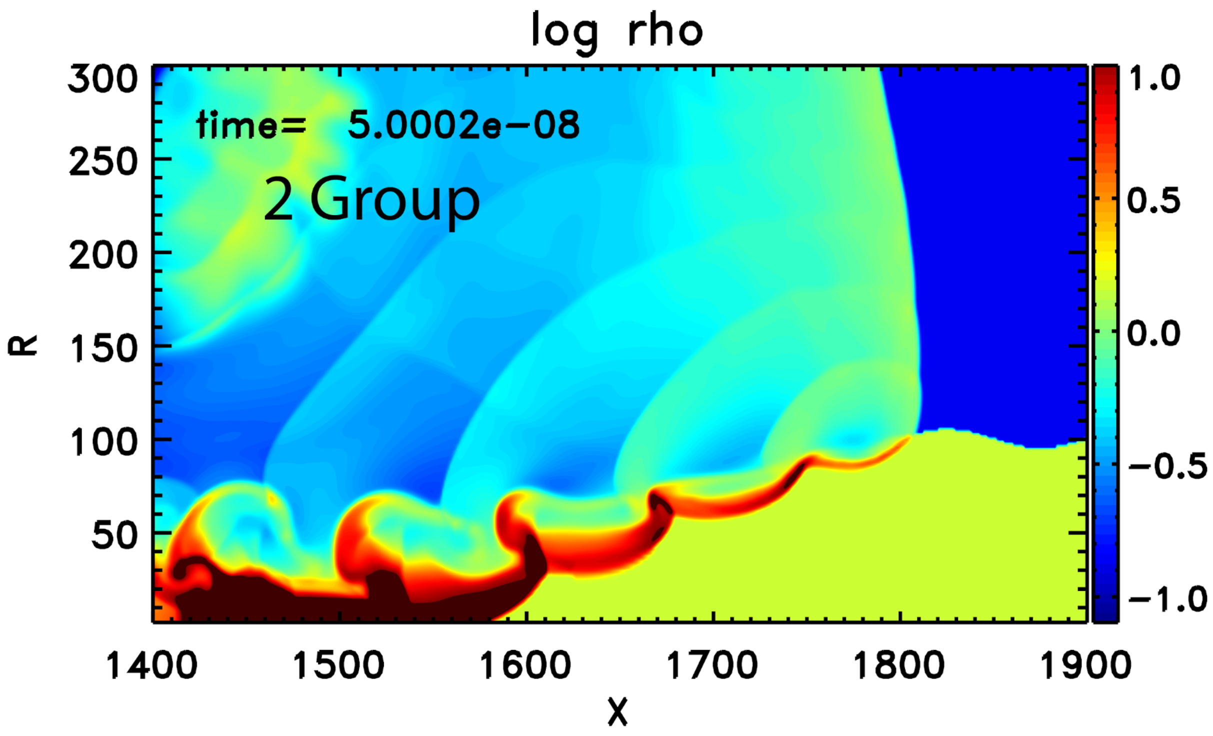
- **accretion shocks, filament shocks**
- **Kelvin Helmholtz instability (KHI)**

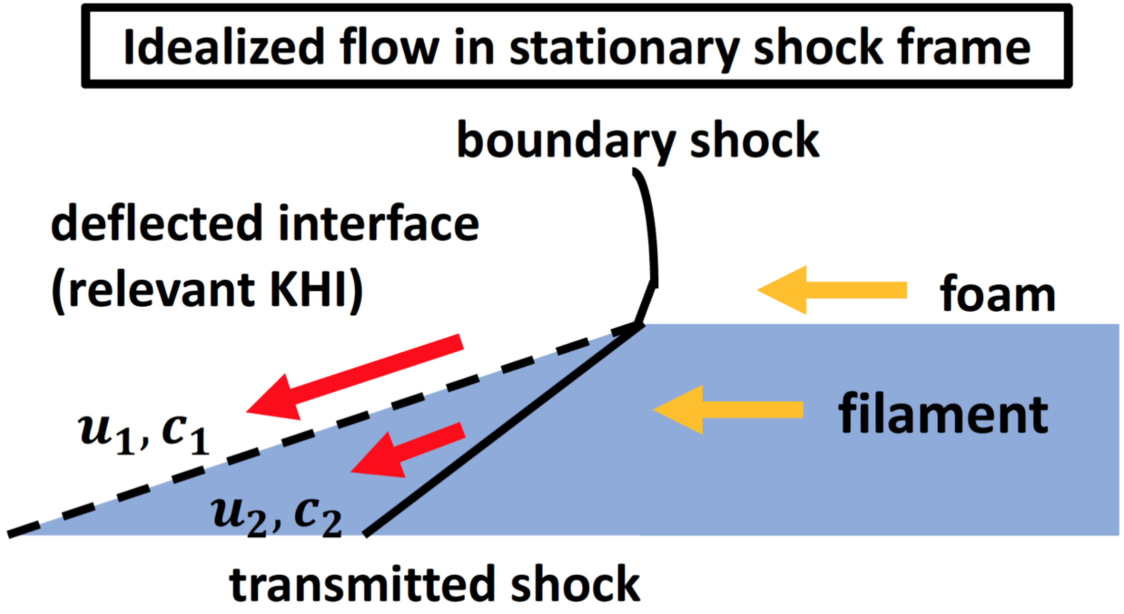
KHI may cause filament breakup before it gets to disc… even before the shock (somewhere between disc & virial radius).

The Omega EP experiment



Exp. shock frame is astrophysical analog





Radiative cooling affects KH, specific scaling

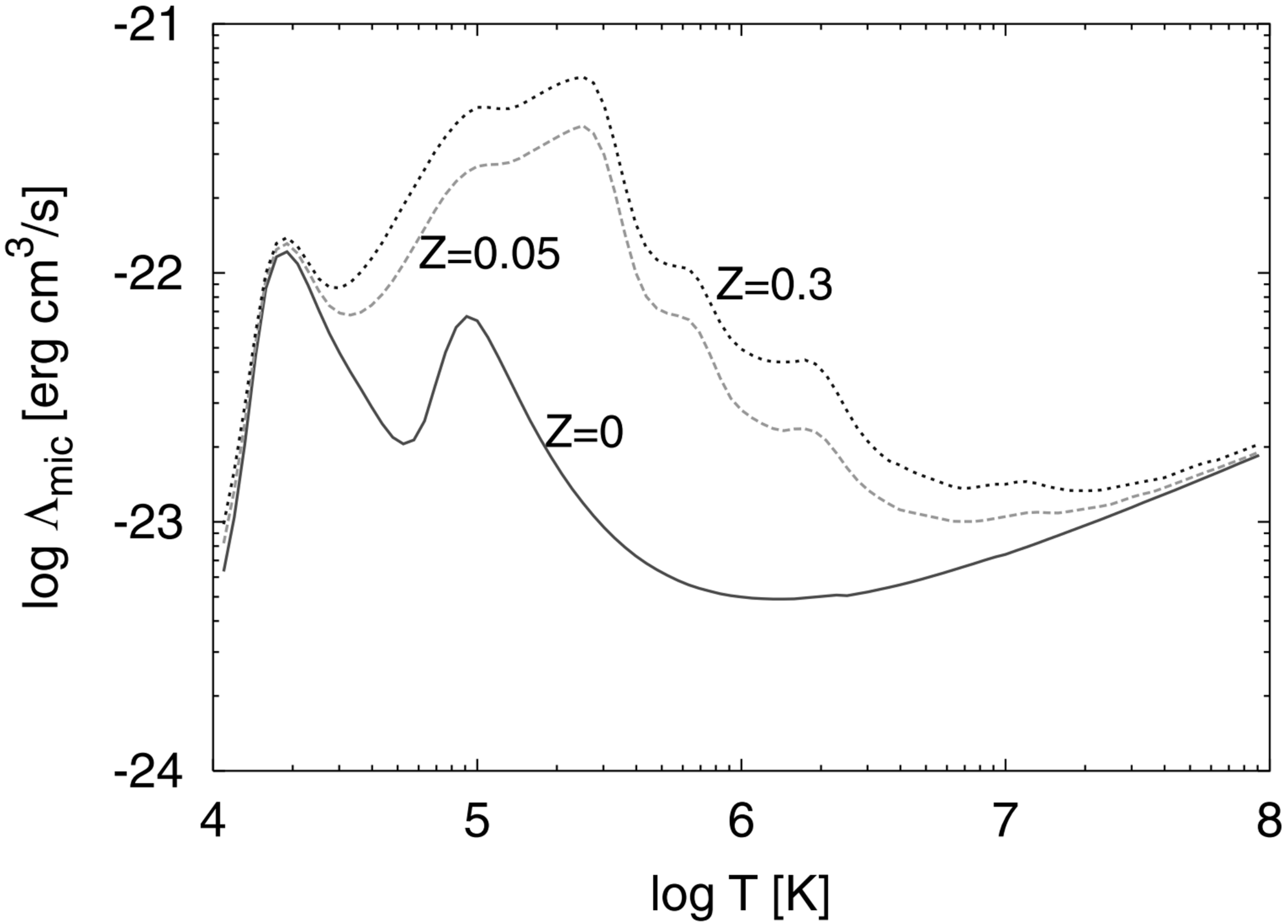
$T_{filament} \sim 10^5$ K, $T_{foam} \sim 10^6$ K,

Cooling is 10 times stronger in shocked filament!

This increases density in shocked layer and stifles KH.

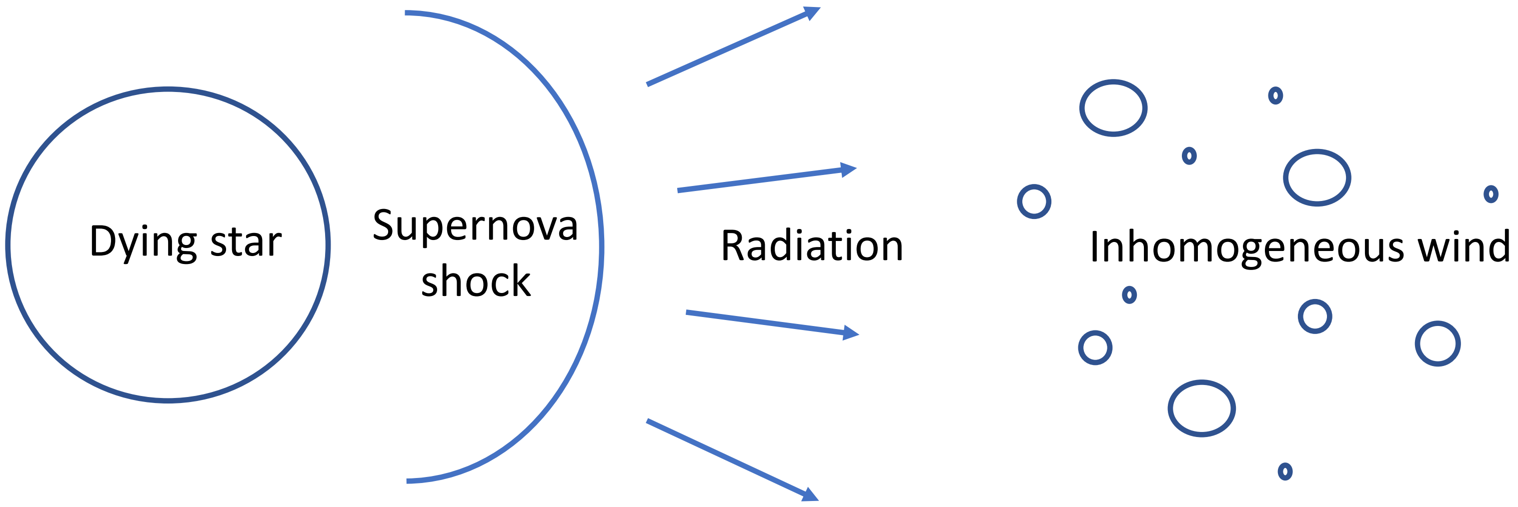
Adiabatic case is BEST case scenario for KH to be effective.

Cooling rate, Z = mass fraction of elements heavier than He, Li



Broader Impact: Why a cosmic filament exp.?

- High impact theory that helps answer fundamental questions about our origin
- Galaxy formation is difficult to observationally explore
- Simulations can resolve filament formation or fine-scale hydrodynamic instabilities, **but often not both**
- **HEDP provides a unique opportunity to investigate firsthand this hydrodynamic phenomenon**



Shock breakout

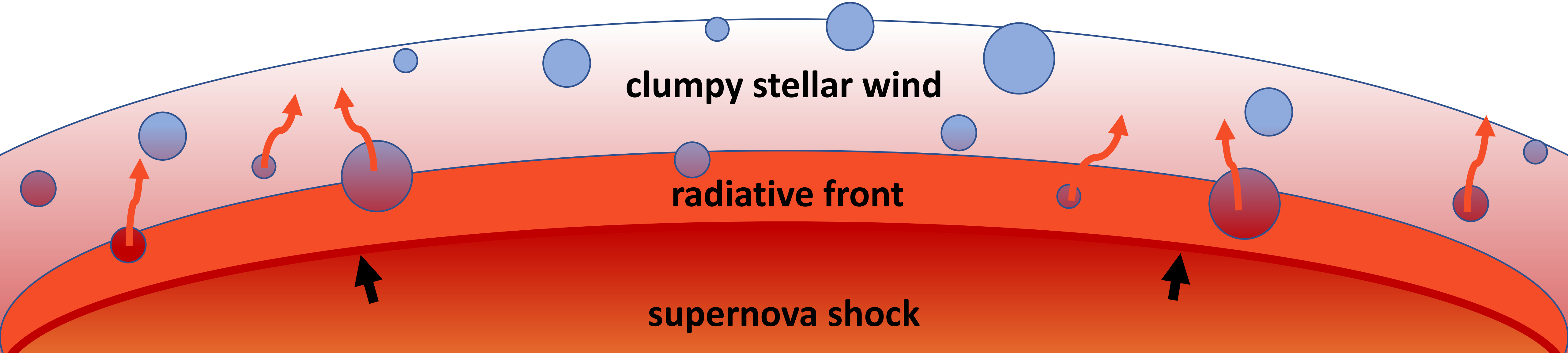
How does radiation from a shock flow through irregular distributions of matter?

Can this process provide us a unique spectral signature for supernovae? For other transient phenomena?

Breakout front turns clumps into emitters

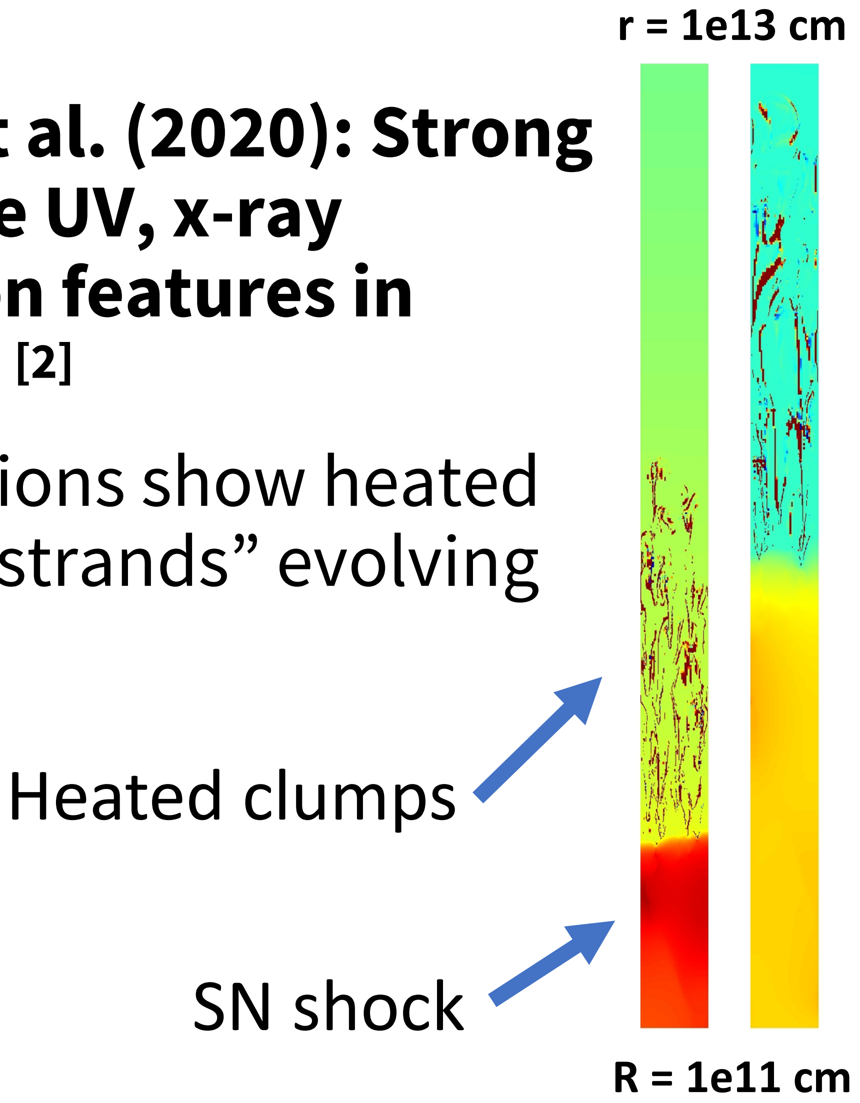
- Radiative shock (~20-60 eV) heats up clumps
- Non-uniform heating, “bright” irregular flow structures
- **Unique spectral signatures? Ingredients:**

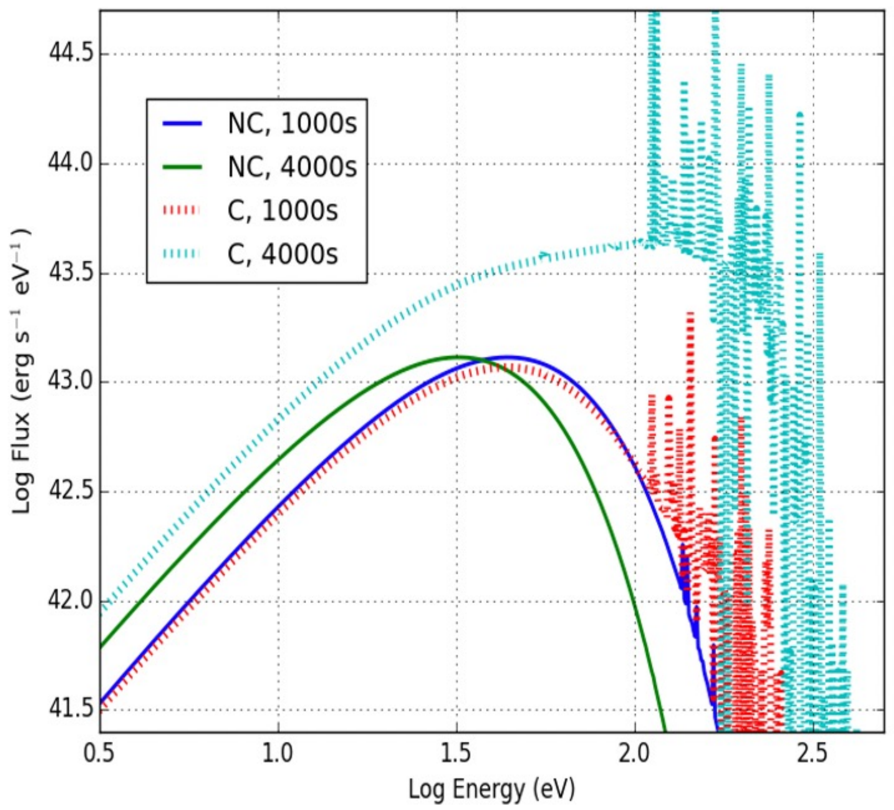
$$\text{luminosity} = f(\text{photon energy}, \text{mass}, \text{opacity}, \text{gas temperature})$$



We've shown enhanced emission in first-look work

- **Fryer et al. (2020): Strong extreme UV, x-ray emission features in spectra [2]**
- Simulations show heated clump "strands" evolving



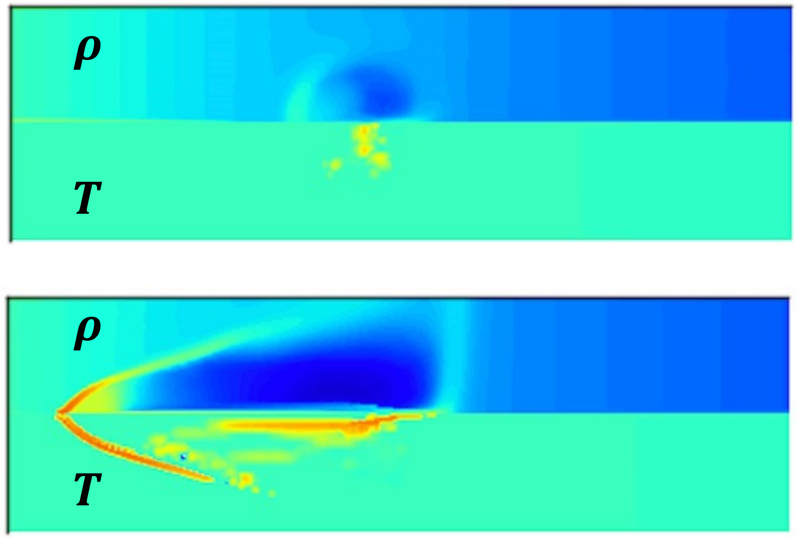


Clumped vs smooth run spectra, note high energy features

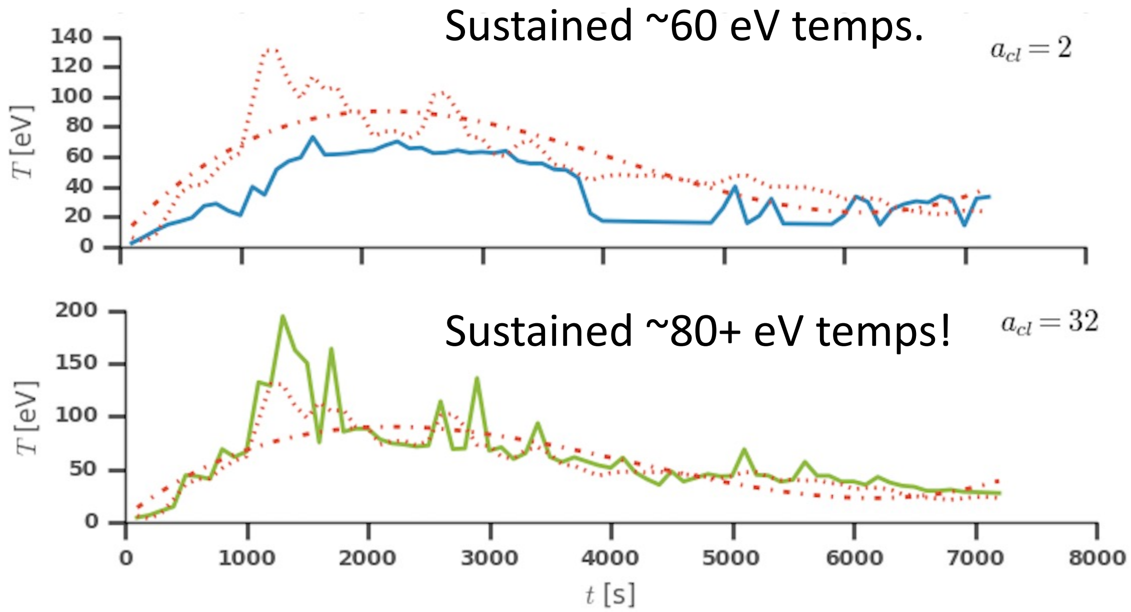
Single sphere studies can isolate the physics

$\rho_{clump} = 2\rho_{wind}$
Low density clump

$\rho_{clump} = 32\rho_{wind}$
High density clump



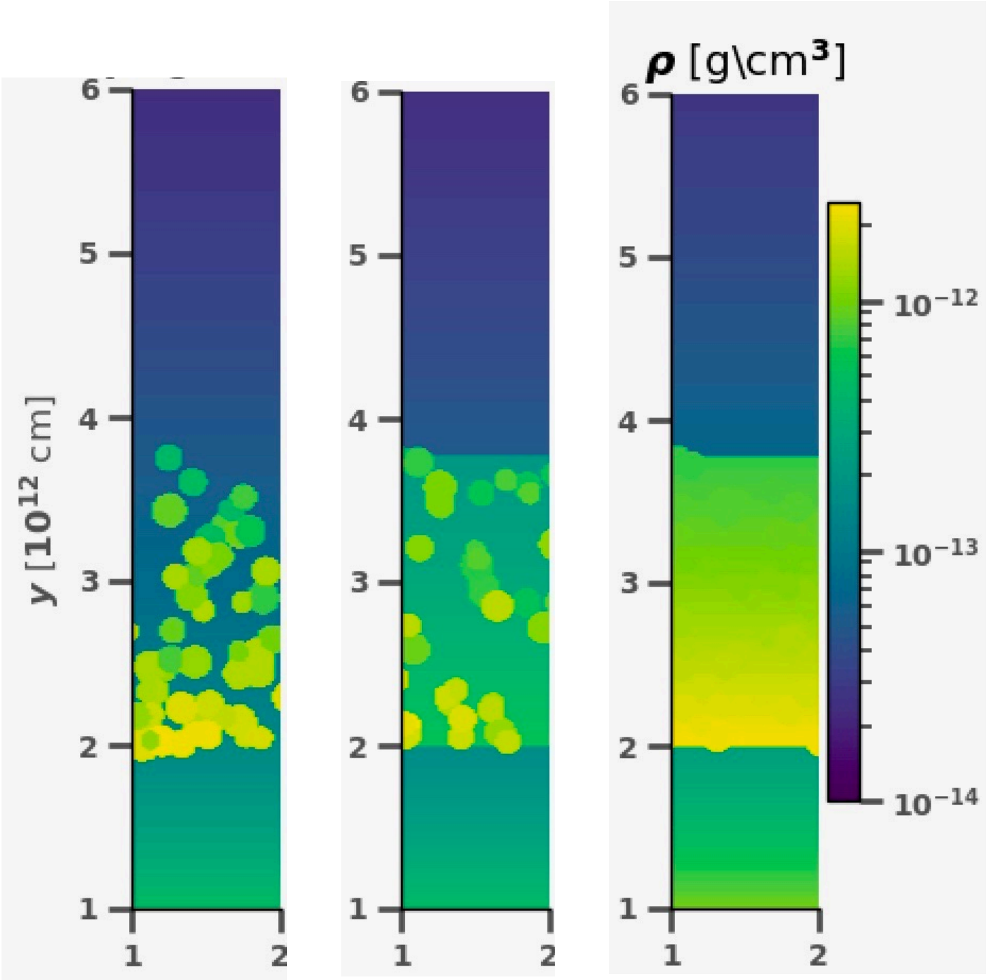
1e12 cm **6e12 cm**



- (Left) density/temperature of clumps.
- (Right) max temperature over time of heated clumps. Red line is an ”average”. **Significant radiative shock heating of denser clumps.**
- **Single (r ~ 1e10 cm) clump, not enough heated mass for spectral signature.**

The porous shell isolates physics in a different way

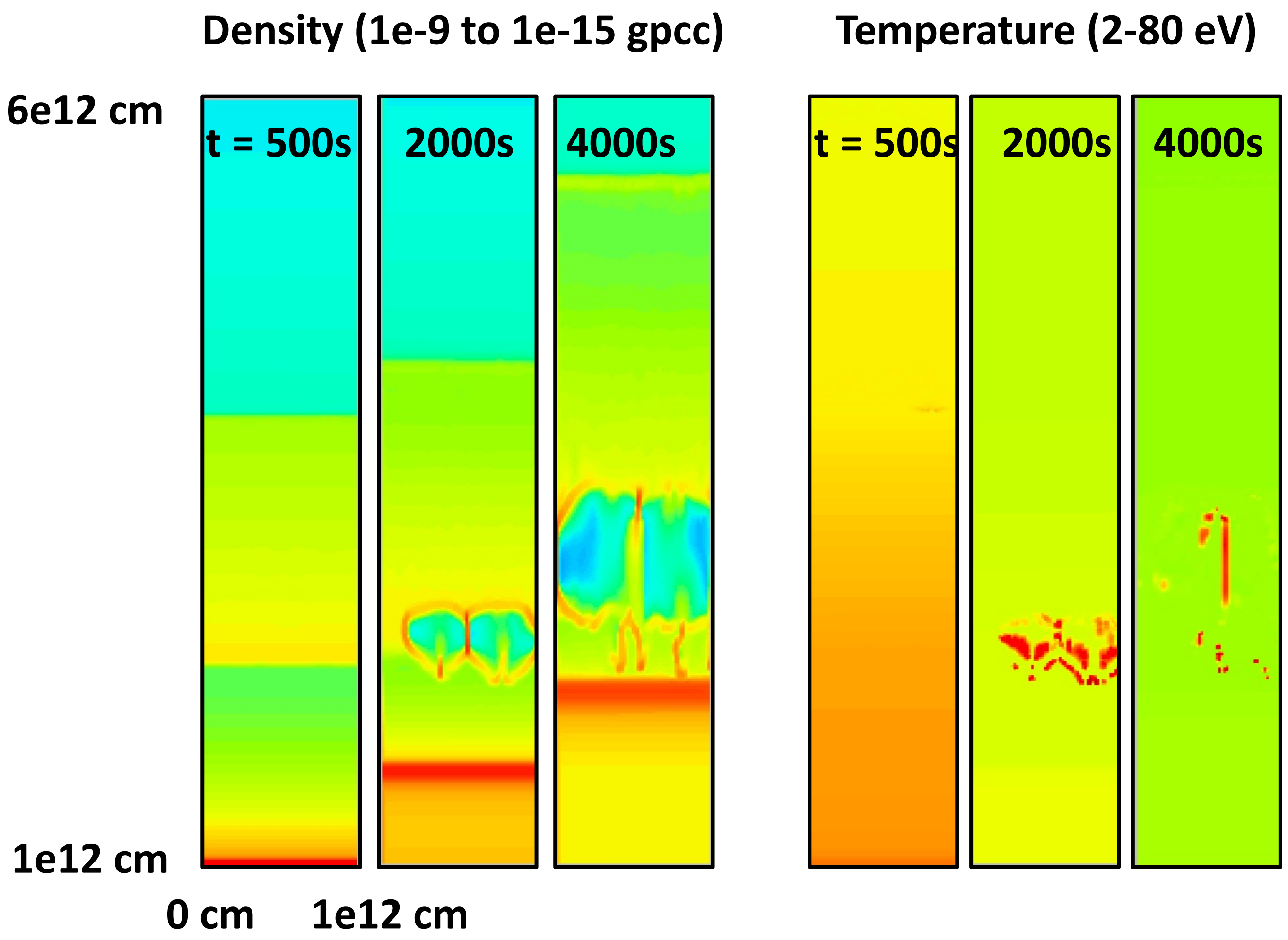
- Putting shell mass into clumps creates porous shell:
  - fixed optical depth
  - increased clump heating
  - porous flow
- May be produced by mass eruptions, convective/rad. instabilities, common envelope ejection …
- We will look at an example of an inner wind shell from 2e12-4e12 cm, seeking extreme UV (EUV) temperatures



pure porous -> pure shell
same avg. optical depth

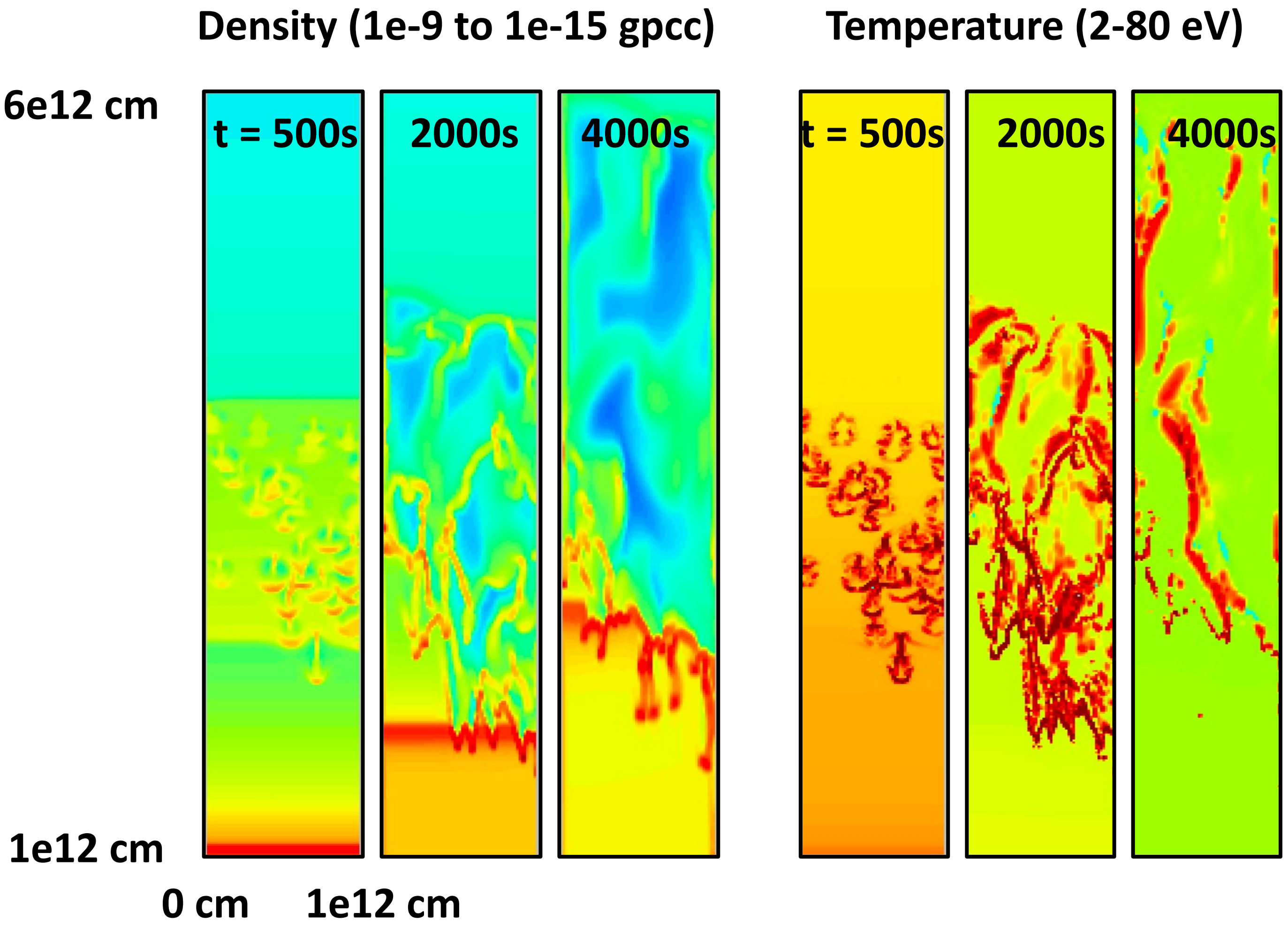
A pure shell SBO doesn't heat enough to EUV+

- LANL's Cassio code
- SN radiation transport
- Nearly solid shell
- 2D strip of a power-law density wind with a porous shell, for 10000 seconds
- 40 eV, 1e9 cm/s shock
- Density plot shows porous structure
- Temperature shows EUV producing temperatures in red
- **This shell does provide enough heated mass!**



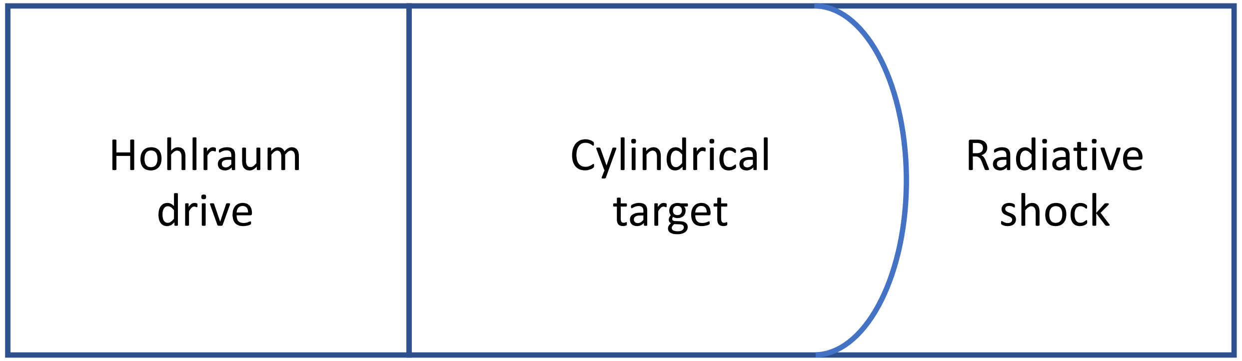
Porous SBO flow creates hot EUV+ emission

- Short lived flow structures
- Radiative acceleration and mixing can shred the clumps, mixing also a cooling process
- **With porous shell, EUV+ temperatures, similar features as pure clumped**
- **More research to be done to discern between spectra**



Broader Impact: Why study shock breakout?

- Constrain supernova mechanisms and environments
- New early X-ray + UV transient satellite missions: **SIBEX and UltraSat**
- **Help explain mechanisms for luminous SN and other transients**
- Radiative shock through porous media in HEDP experiments: **COAX, Radishock**, and others



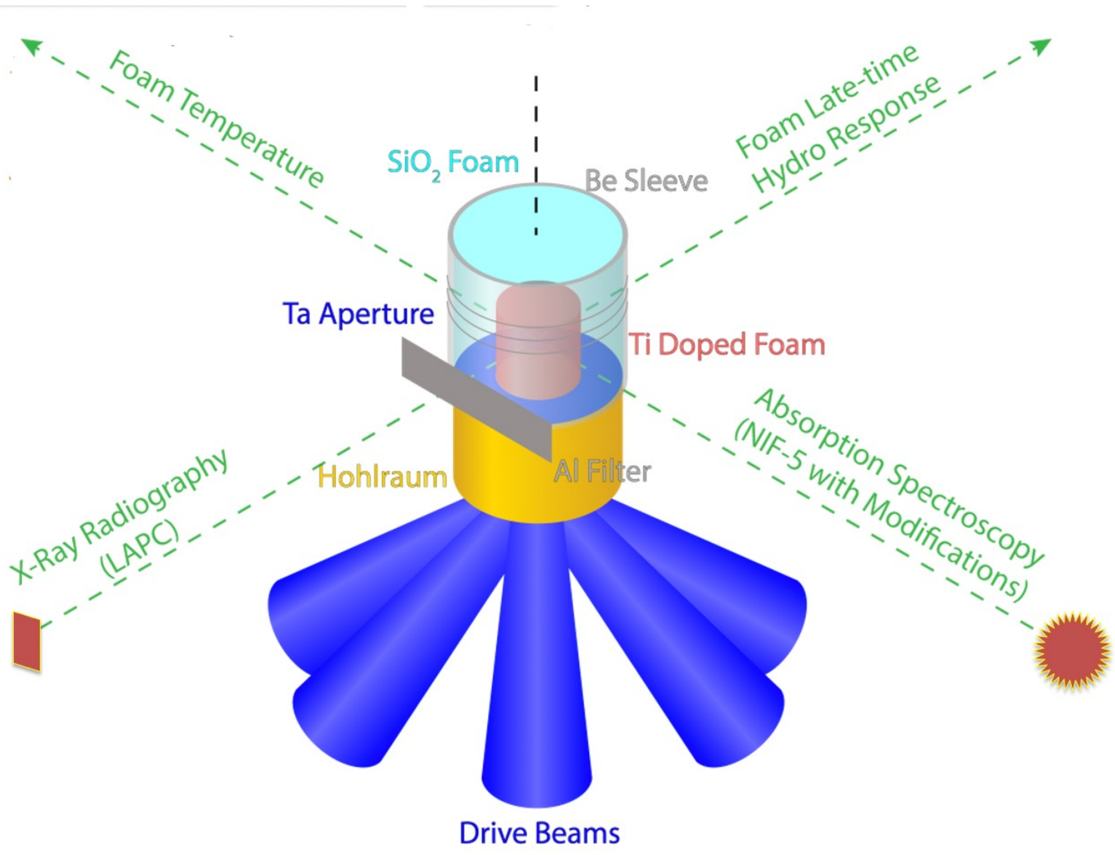
Radiation transport in COAX

Can we simultaneously verify three diagnostics and maximize their data usage?

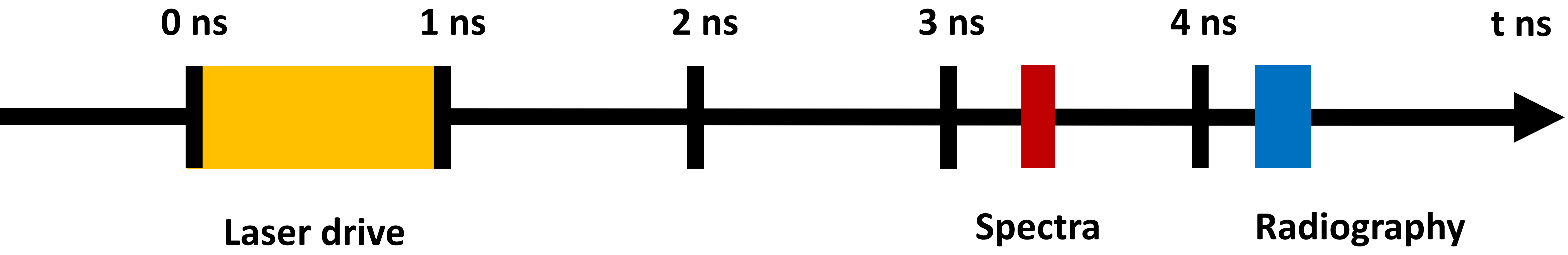
How well will our new spectral diagnostic infer a shock profile temperature?

Is this a good platform for studying shock breakout?

The COAX experiment



- Omega-60 HEDP experiment
- Hohlraum drive sends radiative shock through a Ti doped foam
- Three target types: smooth or **clumped dopants**
- Ti is 15% by mass of target
- Three diagnostics: Dante, radiography, and spectroscopy



In some shots, we look at 0.6 ns drives, but all are roughly 1.0 ns long.

The 5% rise-to-fall time is 1200 ps with a 50 ps error.

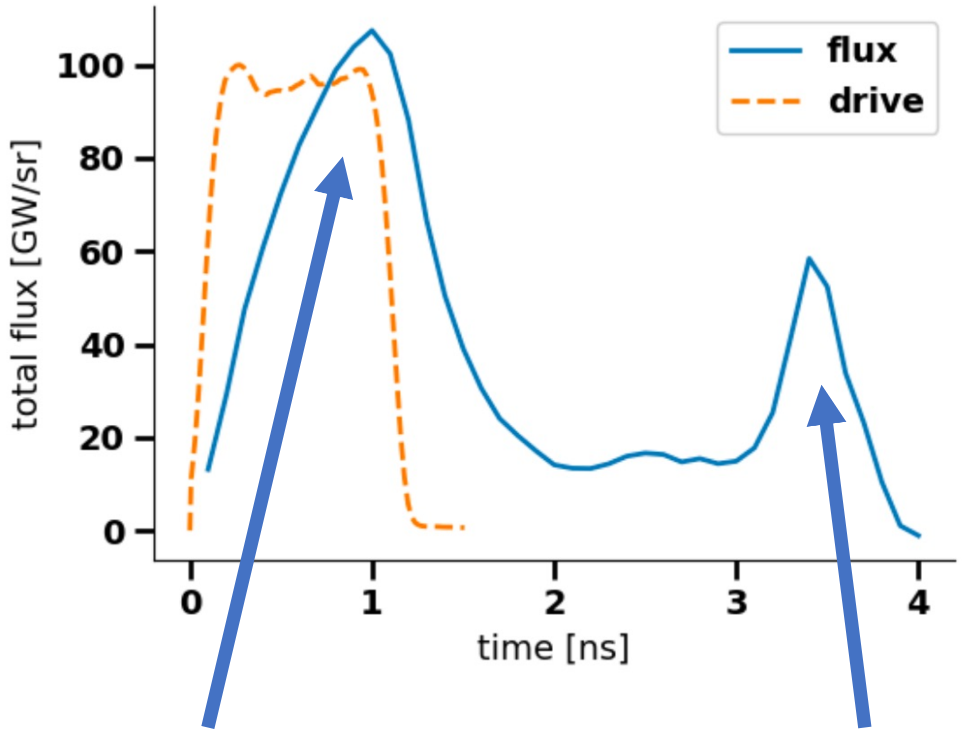
The spectral window is 200 ps.

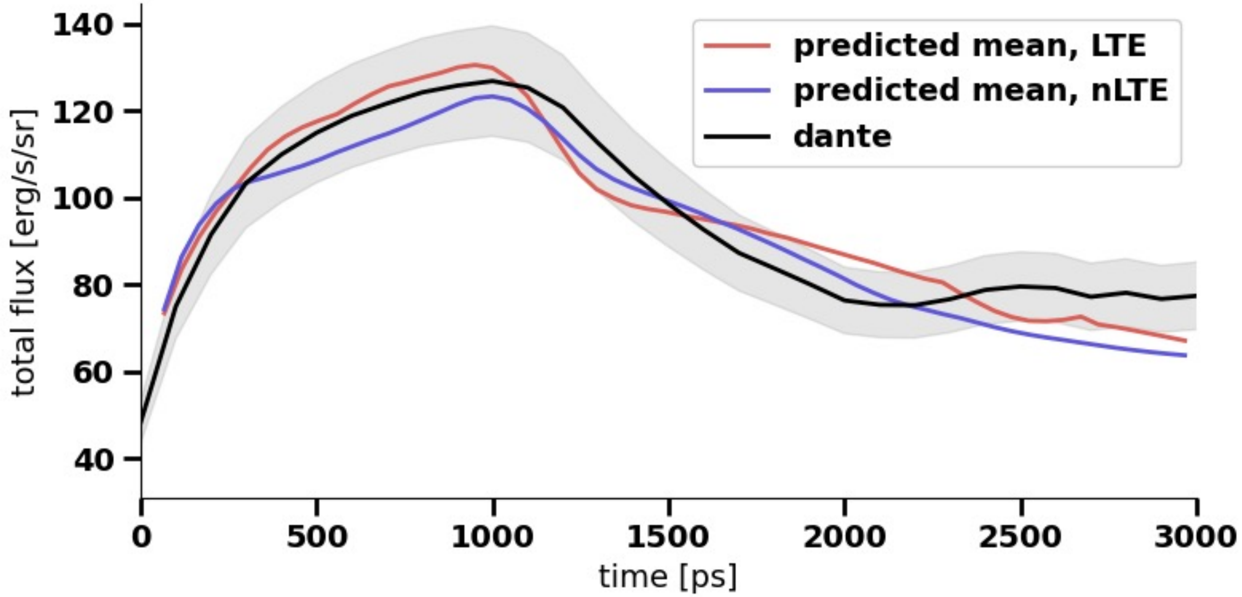
The radiography window is 333 ps.

Radiography is always taken 800 ps after the spectra.

Other radiograph timings are 3.3 ns and 2.3 ns.

Dante is our most qualitative tool





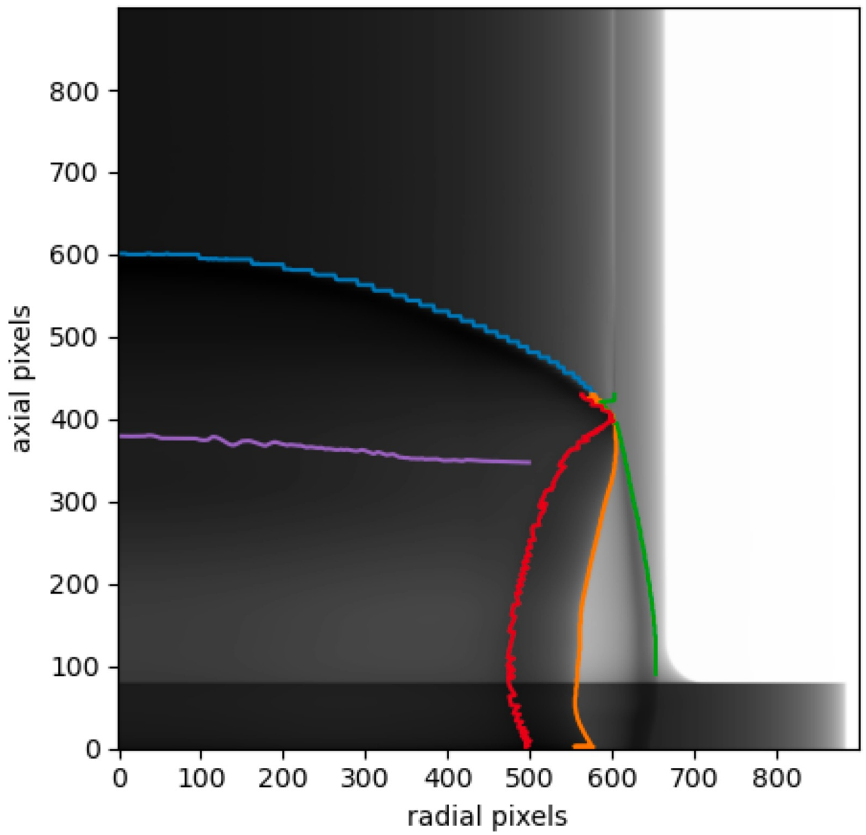
Hohraum drive (orange, not scaled) lasts 1 ns and measured flux (blue) peaks at the end of this drive before cooling.

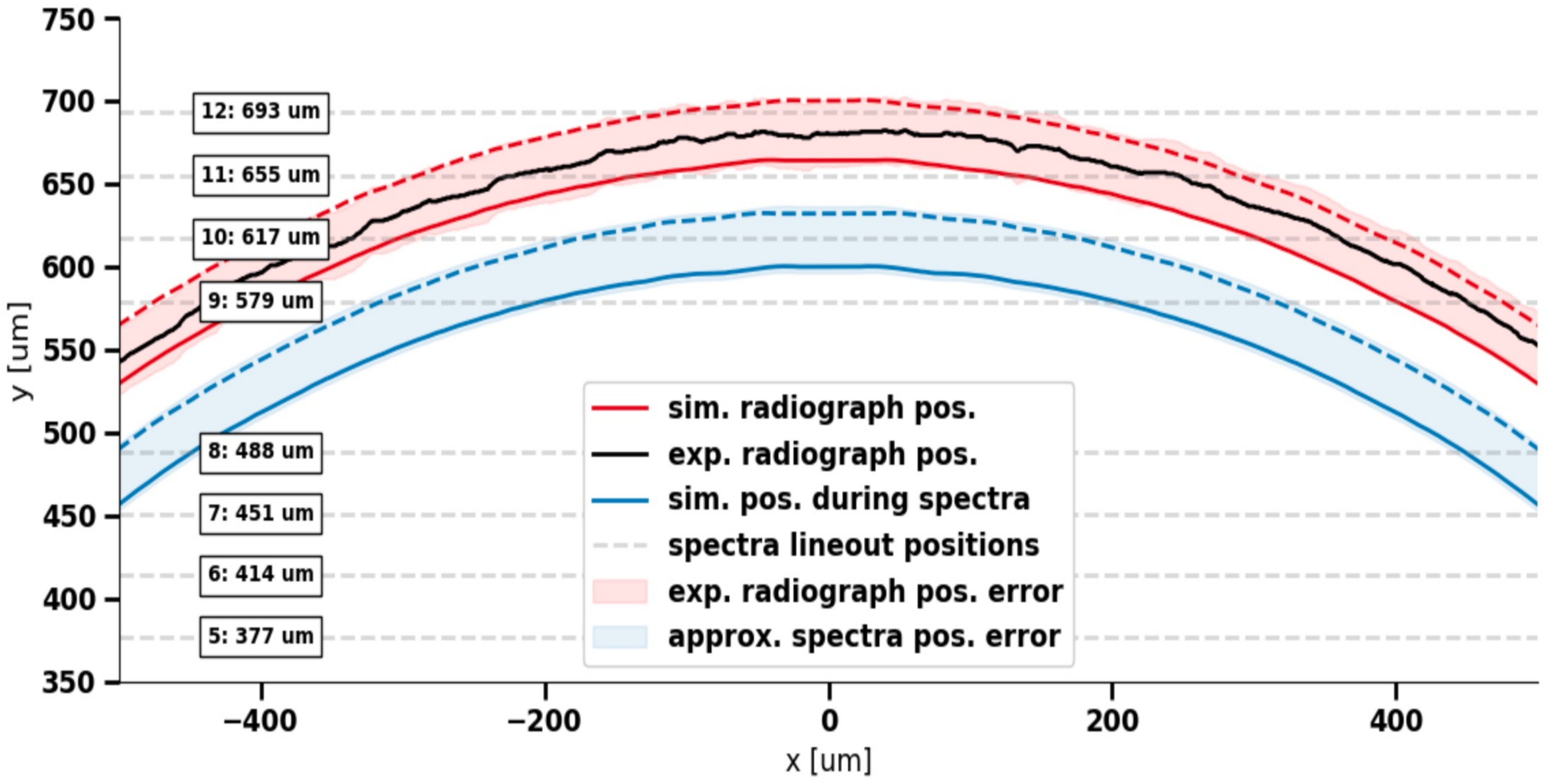
The spectra backlighter for the spectra. We do not know the correct hohlraum T at time of spectra.

We can estimate reasonably the flux from our simulations. BUT

1) The error bounds are likely 20%+
2) Our hohlraum models produce a colder shock than expected!

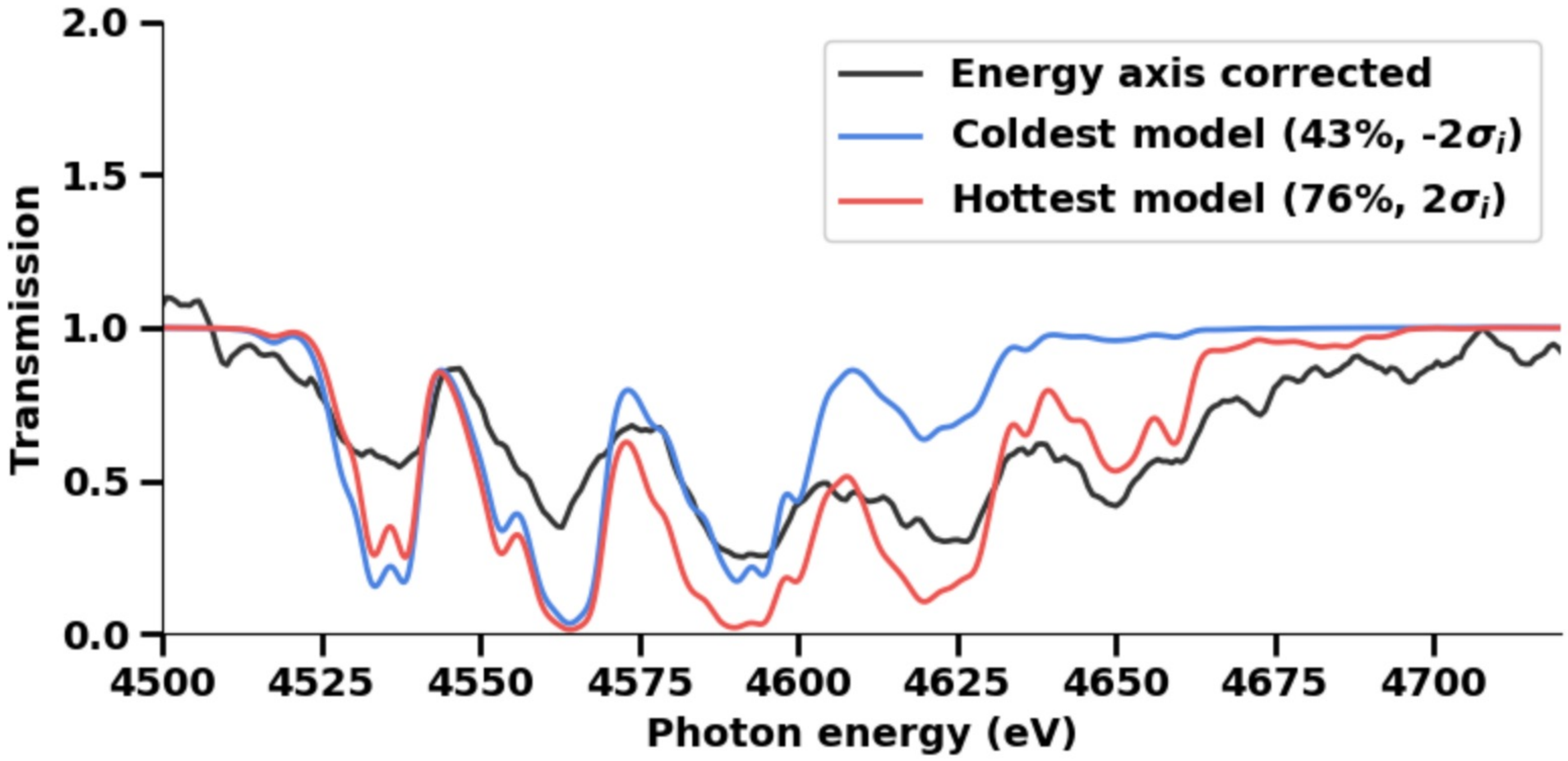
Radiography is our most reliable tool





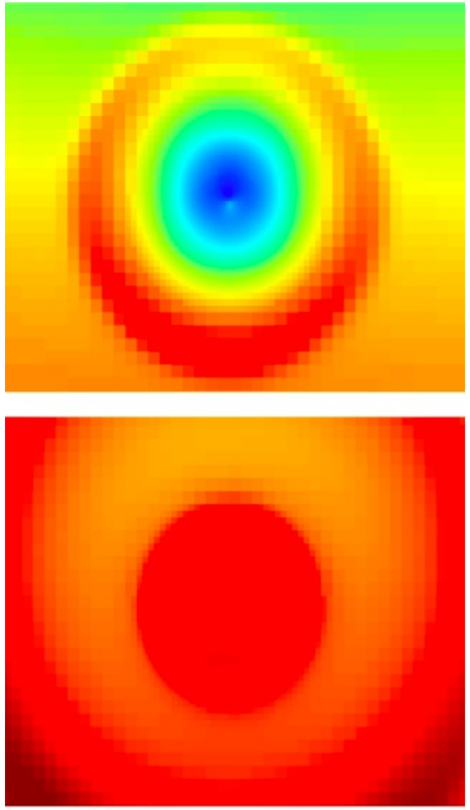
This provides the shock position and curvature and is the basis for all simulation tuning. The plot on the left shows a simulated radiograph and features/curves found reliably with edge detection. The right plot shows the positions of the shock during radiography and spectra as well as the spectral lineout positions.

Spectra is our most revealing tool

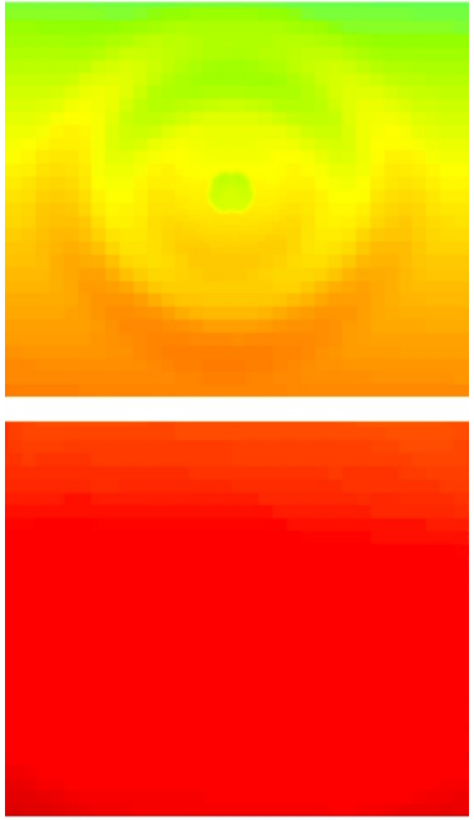


Multiple parameters can produce a "correct" shock position. Spectra comparison tells us our system may not be hot enough! Potentially a damning diagnostic for our modeling capabilities.

Investigating heating of Ti clumps in COAX



- 10 micron (left)
- Radiative front -> drastic heating
- Clump persists after 0.3 ns
- **SN and IMC rad. transport**
- Diffusion model insufficient



- 0.3 micron (left)
- Minimal heating
- Gone by 0.3 ns
- **Similar to breakout phenomenon!**

Key temperature colors: 120 eV 105 eV 85 eV

Broader Impact: Why develop COAX?

- By simultaneously comparing three diagnostics, maximizing data, we push our simulations to the extreme
- Develop our framework for rigorous UQ
- **The new spectral feature can significantly constrain our models**
- **The COAX platform is a testbed for astrophysical processes (breakout, transport in inhomogeneous media)**

Summary

- Developed the scaled theory for an experiment to study KH in filaments feeding galaxies and argued that we provide a best-case scenario
- Performed numerous parameter studies and theory development to understand the physics of supernova breakout
- Systematically modeled COAX to understand
  - diagnostic and simulation uncertainties
  - how to maximize our data
  - and how we can use COAX as a platform for studying radiation transport through inhomogenous media